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The work described in this report summarizes a six-month study to develop a lightweight, tactical electric power plant with a low level of aural, I.R., and visual detectability, based on a Stirling engine. The conceptual design presented was analyzed and predicted to have power output qualities exceeding those specified by the Army for tactical generators. The unit promises to have maintenance and overhaul requirement characteristics superior to any generator system in current use.

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Foreword

This report was prepared at Flow Industries, Inc., 21414-68th Avenue South, Kent, Washington under Contract No. DAAK70-82-C-0046. This project was funded under Phase I of the Defense Small Business Advanced Technology (DESAT) Program. Contract and technical monitoring of the project was provided by the U.S. Army Mobility Equipment Research and Development Command, Electrical Power Laboratory (MERADCOM, DRDME-EM), Ft. Belvoir, VA. The Contracting Officer's representative was Mr. Herb Rothschild (DRDME-FL) and the technical representative was Mr. W. A. Summerson (DRDME-EM).

Acknowledgement

The authors gratefully acknowledge the assistance provided by Mr. W. A. Summerson and Mr. P. Arnold of the U.S. Army Mobility Equipment Research and Development Command, Electrical Power Laboratory (DRDME-EM), Ft. Belvoir, VA for their guidance in defining the design parameters for the Stirling engine mobile electrical generating unit. Also the authors wish to acknowledge Dr. Hung Huynh of Flow Industries, Inc. for performing the computer analysis of the design.

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1. ABSTRACT

The work described in this report summarizes a six-month study to develop a lightweight, tactical electric power plant with a low level of aural, I.R., and visual detectability, based on a Stirling engine. The conceptual design presented was analyzed and predicted to have power output qualities exceeding those specified by the Army for tactical generators. The unit promises to have maintenance and overhaul requirement characteristics superior to any generator system in current use.

2. INTRODUCTION

For several years, the Army has been sponsoring a program to develop a family of Silent Lightweight Electric Energy Plants (SLEEP). The general requirements of the program are to design lightweight, compact, reliable, easily transportable, multifuel electrical generating devices that will be difficult to detect by visual, aural and IR means. The principle uses for the devices will be to provide power for communications equipment, command posts, visual and IR illumination devices, maintenance equipment, ground surveillance radar, battery chargers, and combat vehicle needs.

Developments in Stirling engines over the last several years have made these engines viable candidates for the SLEEP program. The Stirling engine is an external combustion engine, which can run on a multitude of fuels, ranging from the typical military liquid fuels such as gasoline, diesel, JP4 and JP5, to solid fuels such as coal or even wood. This range of fuels greatly enhances the probability that the device will be operational when needed.

Personnel currently involved in major design advances for Flow Industries' Stirling engine program have been actively involved in Stirling technology for over twenty years. Most of these advances have been associated with a program sponsored by the National Institute of Health, in efforts to develop a power source for artificial hearts. The current technology for a Stirling engine heart pump power source is at the stage where a 10-year maintenance-free life is achievable. Operational units have already been running continuously for more than 4 years without maintenance. Critical components in the design have been tested and theorized to have almost infinite life. Studies performed at Flow have demonstrated that the heart power source can be scaled to large engines, as was documented in a report to NASA on scaling up to a 15 kW output model (NASA OR-159587).

The work described in this report was sponsored by the Defense Small Business Advanced Technology (DESAT) program. The total effort is divided into two phases. The Phase 1 portion of the study, presented in this report, was to derive a design methodology that would lead to the development of a Stirling engine-based engine generator set. This report describes a Stirling-Ringbom conceptual design that has a 3 kW electrical power output. The goal of the design effort was to achieve a maintenance-free engine by scaling up the basic heart engine design. Phase 2 of the effort will be to detail the conceptual design of this report and build a demonstration unit.

3. OBJECTIVE

The objective of the work presented in this report was to develop a design methodology that would allow application of Stirling engine technology to engine-generator sets. The work was divided into 3 tasks:

1. Define an end use that will meet the Army's needs, including equipment requirements.
2. Select an engine configuration to meet the requirements as defined above.
3. Evaluate the feasibility of the selected engine configuration.

The effort described here covers a six-month period. A conceptual design meeting the requirements developed in Task 1 above is presented, and forms the basis for a Phase 2 effort, which will be the construction of a demonstration unit.

4. APPROACH

In order to best define the Army's needs, a review meeting was held with MERADCOM personnel at Ft. Belvoir, Virginia. Discussions resulting from this meeting established a set of requirements for a power plant that would best meet the Army's needs. The SLEEP program was identified as a good application for Stirling engine technology.

Once a general set of requirements was established, a review of past work in Stirling engine development was made by drawing from experience gathered during 15 years of work by Flow personnel on a Stirling heart pump. After comparing the Army's requirements for a Stirling-powered generator with the capabilities of state-of-the-art Stirling technology, a comparative analysis was performed on five Stirling engine concepts. We then selected the best of these concepts, determined preliminary sizing and specifications, and produced a conceptual layout. Next, we performed a computer analysis of operation under startup, steady state and transient conditions, and the results were compared with the requirements set by MIL-STD-1332B.

5. DISCUSSION

A. Army Requirements

The Army's requirements were identified as a result of discussions with MERADCOM personnel, and were based on the SLEEP program. They are aimed at developing a lightweight, low detectability, tactical electrical power source. Eight points for consideration were brought out in the discussions. They are:

1. Selection of the working fluid (air, hydrogen or helium).
2. Power density characteristics of the kinematic versus Ringbom designs.
3. Efficiency.
4. Trade-offs (e.g., performance versus field serviceability).
5. Serviceability.
6. Ambient temperature and altitude in service conditions.
7. Fuels (gasoline, diesel, JP4 and JP5).
8. Cost.

These points are covered in this section as part of the various design considerations and trade-off studies. The range of engines applicable to the study covered 0.5 kW to 10 kW. As a result, the study concentrated on a 3 kW design, since this was in the middle of the size range and could be easily scaled up or down to cover the limits. This section presents the results of the study and addresses the points listed above.

B. Stirling Engine Concepts Reviewed

Five free piston Stirling engine concepts were reviewed and are summarized as follows:

1. Free piston with linear alternator output.
2. Free piston with hydraulic power output.

3. Forced displacer with free power piston, and hydraulic output.
4. Free displacer Ringbom with rotary crank output.
5. Forced displacer Ringbom with rotary crank output.

Tables 1 through 5 and Figures 1 through 5 compare the five Stirling designs considered in Phase 1.

Five criteria were selected for evaluation:

. Noise level: Stirling engines do not have the combustion noise problems associated with internal combustion engines. They do have limited combustor noise, which can be easily muffled. The predominant noise comes from the cooling fan. One means to overcome this noise problem is to use a large diameter, low speed fan with acoustic treatment on the shroud. Efficient fan designs will also help reduce the sound level. In general, the Stirling engine should be very quiet, as a result of inherent low noise levels and the use of standard noise reduction techniques.

. Performance: The performance of the Stirling engine is very high compared to other engines. For the 3 kW range, an efficiency of about 40% should be achievable. Higher efficiencies could be expected for larger engines.

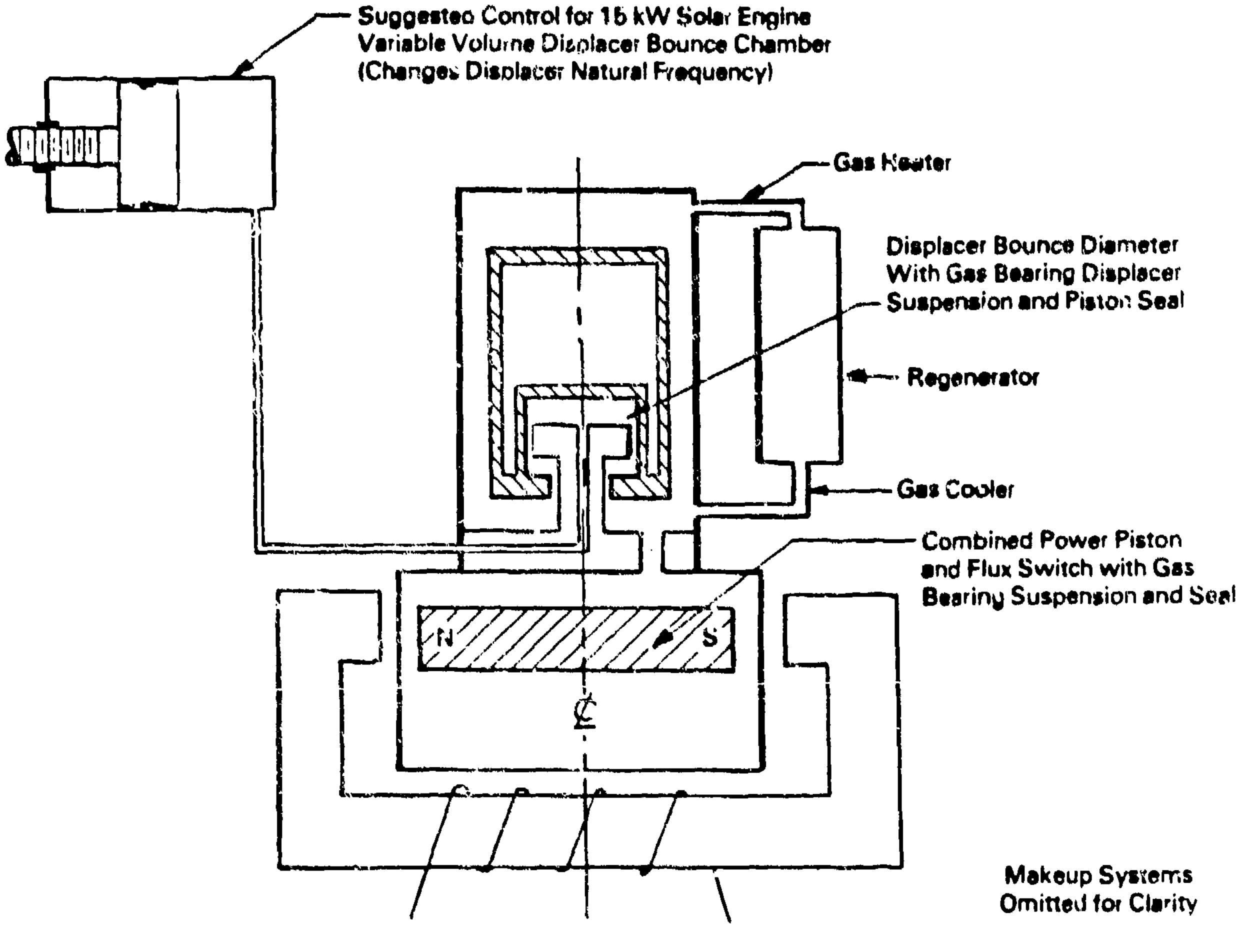
. Reliability: The Stirling heart power source program has demonstrated that very reliable Stirling engines can be built. The novel design techniques developed for the heart engine can be used for an electrical generator unit. These designs actually reduce production costs when compared with less reliable designs.

. Transportability: The power density of the Stirling engine becomes quite high when using helium and a high working gas pressure. This translates into a very portable, lightweight design. A 3 kW unit meeting the Army's service standards will weigh less than 300 pounds.

. Maintainability: The design concepts presented in this report allow the entire engine/alternator assembly to be sealed much like a home refrigerator compressor unit. This would produce years of trouble-free service. By combining the engine/alternator unit with other modular units, maintenance can be greatly simplified. The combination of high reliability and low maintenance will greatly enhance the availability of the unit, and assure its mission-ready status.

Table 1. Flow Industries Evaluation of the *Free-Piston Stirling Linear Alternator Concept*

Organization:	MTI	
Examples:	a)	3 kW Free Piston Stirling Engine Generator Study for U.S. Army Mobility Equipment Research and Development Command under Contract DAAR 70-81-C-0115
	b)	15 kW Solar Electric Free Piston Stirling Linear Alternator Study under NASA Contract DEN3-56
Features:	a)	Free piston linear-alternator concept
	b)	Gas bearing support of moving components
	c)	Gas bearing piston seals
Advantages:	a)	Simple concept
	b)	Two moving parts plus moving components in the control system.
Disadvantages:		Flow Industries extensively analyzed an MTI 15 kW free piston Stirling linear alternator system in conjunction with NASA funded study which explored coupling a hydraulic converter, hydraulic motor, and rotary alternator to the engine. This study revealed the following disadvantages of the free piston Stirling linear alternator approach.
	a)	Self-sustained oscillation is only marginally stable for this configuration. At many desirable design points and possible load conditions, the engine will not run.
	b)	Holding constant operating frequency with varying power output is difficult.
	c)	Gas bearing seals and supports for moving components are expensive and compromise reliability.
	d)	System is unable to operate at resonance without unacceptable displacer collisions. This limits operation to subresonance, which limits power density and efficiency, and increases weight, volume, and cost.
	e)	Use of annual heater head with high thermal stress coefficient limits design to low pressure, which limits power density and efficiency, and increases weight, volume, and cost.
	f)	Low average flux-cutting speed of linear-alternator increases generator weight and the required amounts of expensive magnetic materials. This affects system weight, volume, and cost.
	g)	Use of the generator armature as the engine power piston places constraints on the engine design not imposed by other approaches, thereby increasing weight, volume, and cost.

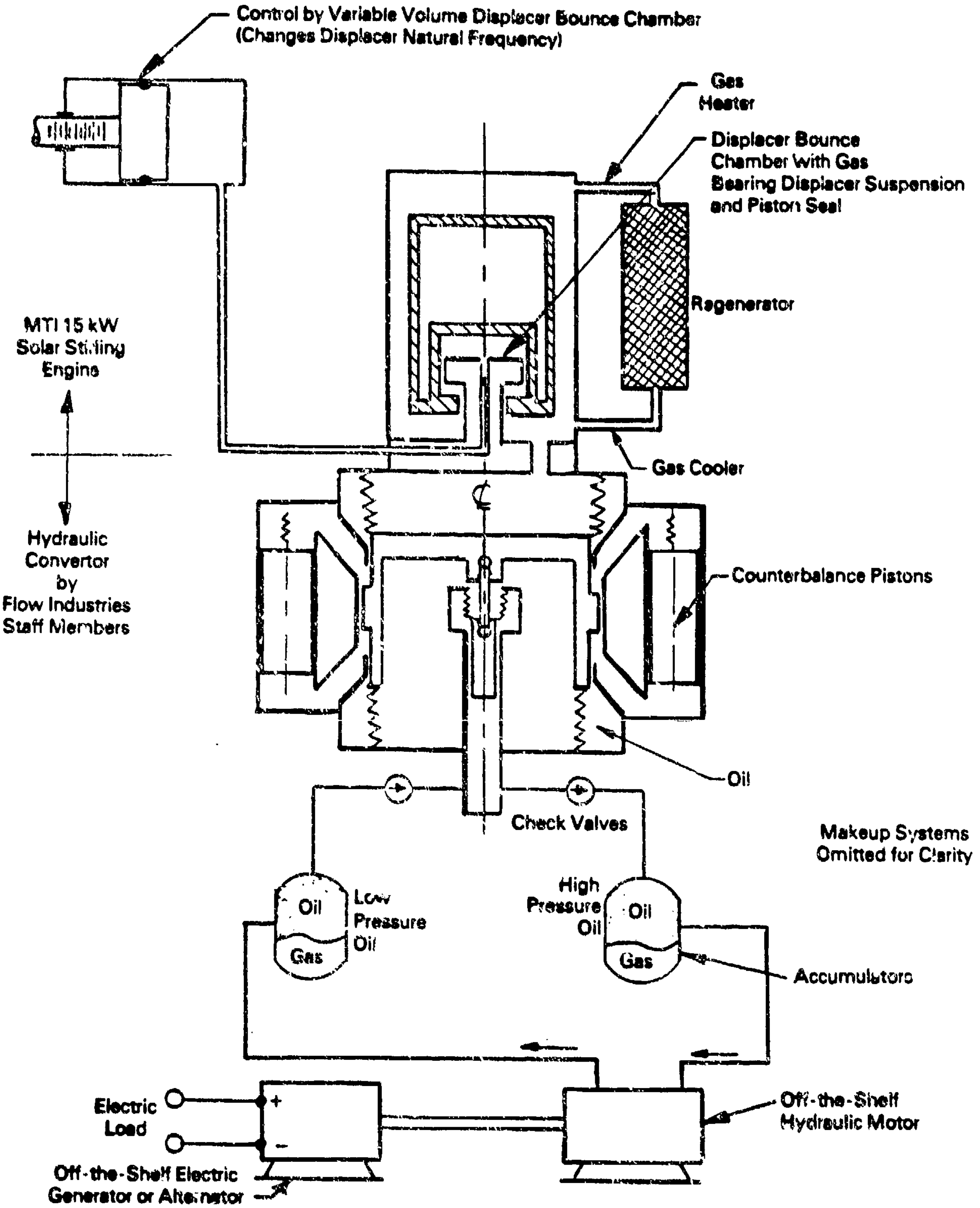


Concept Diagram, Free Piston Stirling Engine with Linear Alternator

Figure 1

Table 2. Flow Industries Evaluation of the *Free Piston Stirling Hydraulic System Concept*

Organization:	University of Washington, Joint Center of Graduate Study (JCGS)
Example:	Free piston Stirling hydraulic engine for Artificial Heart Power Source Project funded continuously by NIH since 1967. Development has progressed to an advanced stage with high performance and many years of continuous life testing with engines and critical components.
Organization:	Flow Industries/JCGS (Contractually constrained to MTI engine portion design)
Example:	Conceptual Design and Cost Analysis of Hydraulic Output Unit for 15 kW Free Piston Stirling Engine. NASA Lewis Research Center, Contract DEN3-212. The engine used in this conceptual design was an MTI 15 kW design originally intended for use with a linear alternator. Dynamics of both the Stirling hydraulic approach and the Stirling linear alternator approach were studied extensively.
Features:	a) Proprietary "dry inertia" power piston. Pressure-balanced, fully-lubricated power piston, sealed by hermetic pressure-balanced metal bellows. b) Uses gas bearing for displacer drive seal. c) Uses off-the-shelf hydraulic motor and off-the-shelf generator or alternator. d) Power piston motion dynamically balanced. Displacer piston motion unbalanced.
Advantages:	a) Retains many of the advantages of the demonstrated Stirling hydraulic approach developed for long life artificial heart power source application. b) Off-the-shelf hydraulic motor and electric generator or alternator require no development. c) Generator frequency is decoupled from engine frequency, allowing practical control to maintain constant frequency.
Disadvantages:	a) Self-sustained oscillation is marginally stable. At many desirable design points and possible load conditions, the engine will not run. b) Gas bearing displacer drive seal and support is expensive and may compromise reliability. c) Compromised power density. Cannot operate at resonance without experiencing displacer and power bellows collisions. d) Partially unbalanced. Cannot employ dynamic absorber because operating frequency shifts with power level.

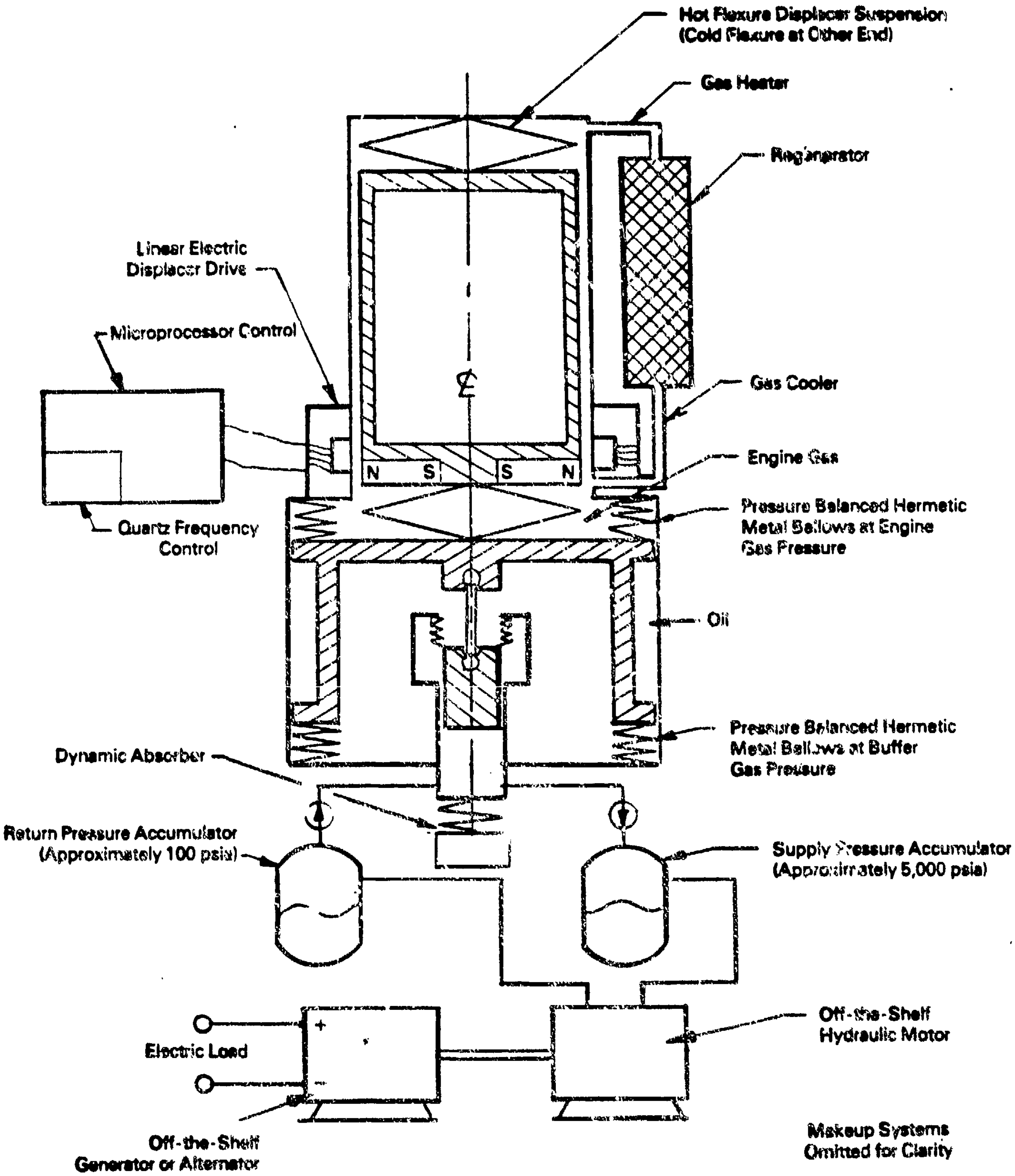


Free Piston Stirling Hydraulic Concept Based upon a 15 kW Solar Engine Study for NASA Using an MTI Engine and a Hydraulic Convertor by Flow Industries Staff Members

Figure 2

Table 3. Flow Industries Evaluation of the *Forced Displacer, Free Power Piston Stirling Hydraulic System Concept*

Organization:	Flow Industries
Example:	External Drive Research Engine developed and tested successfully by University of Washington, Joint Center for Graduate Study.
Features:	Same as free piston Stirling hydraulic except displacer is driven from external energy source. Displacer drive is independent of engine pressure fluctuations.
Displacer Drive Alternatives:	a) Rotary electric b) Rotary hydraulic c) Linear electric d) Linear hydraulic
Advantages:	a) Outstanding potential for long mean-time-between-overhauls and failures, low weight, low volume, and low cost. b) Retains many of the advantages of the demonstrated Stirling hydraulic approach developed for long life artificial heart power source application. c) Off-the-shelf hydraulic motor and electric generator or alternator require no development. d) Numerous possible stable approaches to control have been identified. Linear displacer drive approaches reduce both Carnot heat and reheat losses at part power. e) Operating frequency is easily made constant for both rotary and linear displacer drive, allowing use of a dynamic absorber for full system balancing or for augmentation of system balancing. f) Linear electric drive of displacer allows independent control of displacer amplitude, providing operation at resonance without displacer or power train collisions. Operation at resonance increases power density, thereby reducing weight, volume, and cost. g) Linear electrical displacer drive eliminates need for displacer drive piston seal. h) Proprietary Flow Industries heater head design allows high design pressure for high power density and efficiency and low weight, volume, and cost.
Disadvantages:	a) Requires hydraulic accumulators.

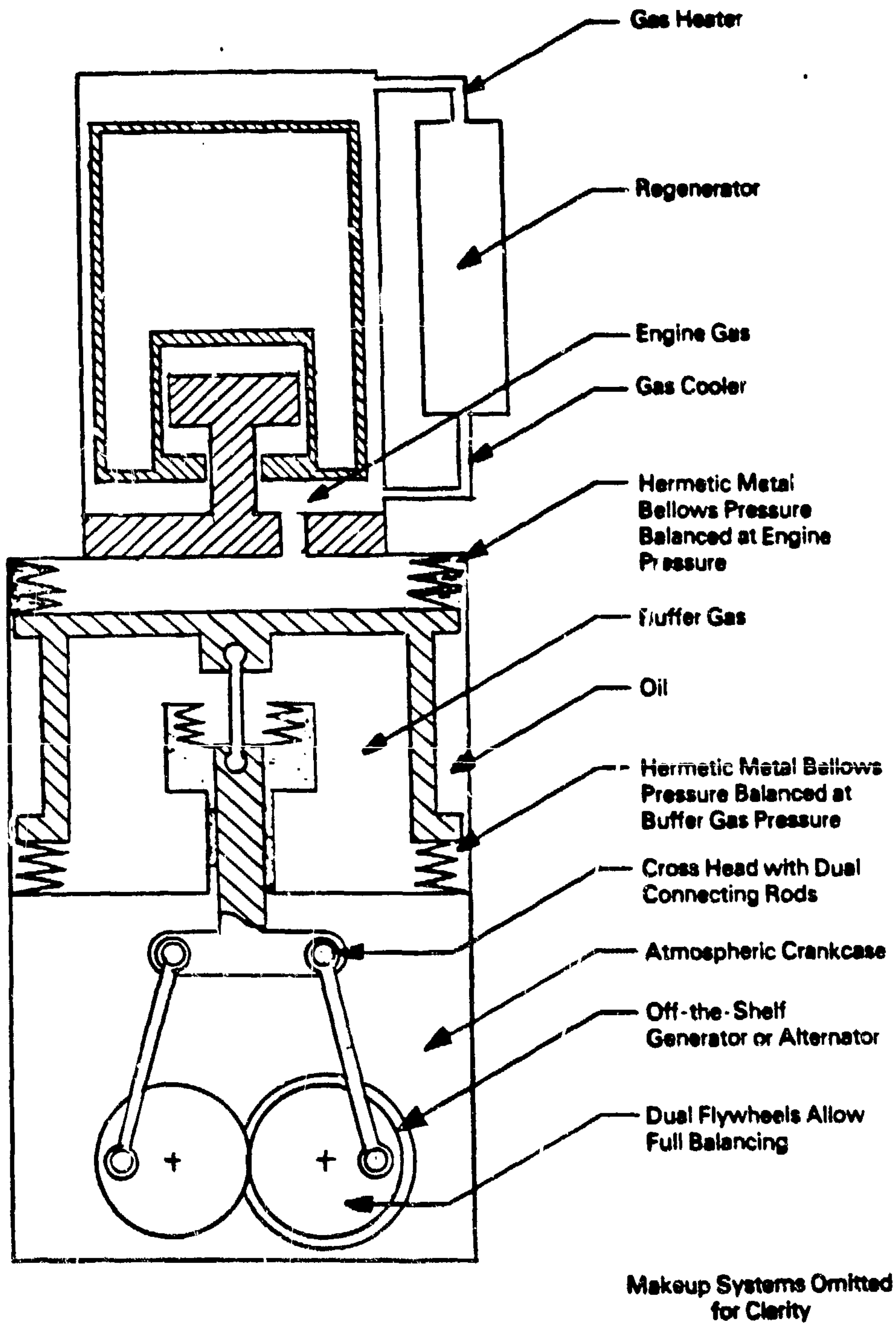


Forced Displacer, Free Power Piston Stirling Hydraulic Concept with Microprocessor Controlled Linear Electric Drive System

Figure 3

Table 4. Flow Industries Evaluation of *Free Displacer Ringbom Electric System Concept*

Organization:	Flow Industries
Features:	Same as free piston Stirling hydraulic except power piston is coupled directly to rotary motion. a) Crank or yoke connects pressure-balanced power piston with flywheel, which drives generator or alternator. b) Counter-rotating flywheels for complete dynamic balance. c) Overdriven free piston displacer drive with top-end tuning. d) Off-the-shelf rotary alternator or generator. e) Hydraulic motor is not required.
Advantages:	a) Pressure-balanced power piston greatly reduces power train bearing loads, power-train friction losses, and required flywheel mass. b) Retains many of the advantages of the demonstrated Stirling hydraulic approach developed for long life artificial heart power source application. c) Off-the-shelf alternator or generator requires no development. d) Completely balanced for smooth, quiet, vibration-free power.
Disadvantages:	a) Control mode to provide precise frequency control not identified. b) Two small flywheels are required. c) Displacer drive piston seal not identified. Gas bearing shown in concept diagram considered unacceptable for reasons of cost and reliability.

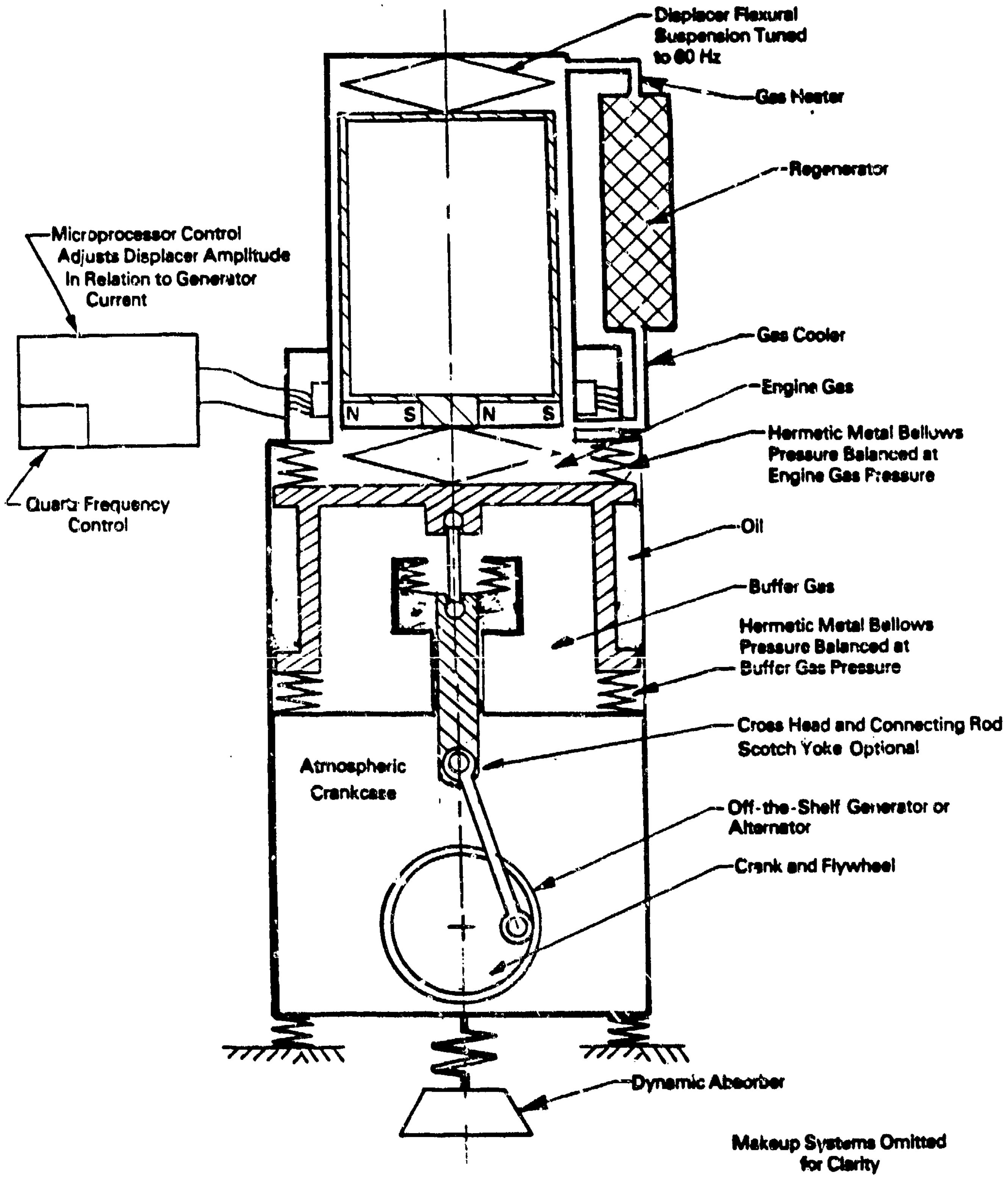


Free Displacer Ringbom Electric Concept

Figure 4

Table 5. Flow Industries Evaluation of *Forced Displacer Ringbom Electric System Concept*

Organization:	Flow Industries
Features:	Same as free displacer Ringbom except that the displacer is driven from an external energy source. The displacer drive is independent of the engine pressure fluctuations, allowing steady operation at a specified frequency, regardless of the load.
Displacer Drive Alternatives:	a) Rotary electric b) Rotary Hydraulic c) Linear electric d) Linear hydraulic
Advantages:	a) Outstanding potential for long mean-time-between overhauls and failures, low weight, low volume, and low cost as demonstrated by the long-life, artificial heart power-source application. b) Pressure-balanced power piston greatly reduces power train bearing loads, power train friction losses, and required flywheel mass. c) Retains many of the advantages of the demonstrated Stirling hydraulic approach developed for long-life, artificial heart power-source application. d) Off-the-shelf alternator or generator requires no development. e) Completely balanced for smooth, quiet, vibration-free power. f) Proprietary Flow Industries heater head design allows a high design pressure for high power density and efficiency, and low weight, volume, and cost. g) Numerous possible stable control approaches have been identified. One simple control concept is a displacer drive using a synchronous motor. The engine operates at constant frequency with engine torque automatically adjusting to load torque. Engine reheat loss does not decrease at partial load, but Carnot heat does. The linear displacer drive alternatives allow microprocessor control of the stroke, while maintaining a constant frequency. The linear drive reduces both reheat loss and Carnot heat when operating at partial power. h) Linear Electrical displacer drive approach eliminates the need for displacer drive piston seal. i) Operating at a constant frequency allows the use of a dynamic absorber for full system balancing or augmentation of system balancing. If a dynamic absorber is used for full system balancing, only one flywheel is required.
Disadvantages:	a) One small flywheel is required.



Forced Displacer Ringbom Electric Concept Shown with Linear Electric Displacer Drive

Figure 5

Displacer control techniques were examined and classified into two categories: (a) free displacer; and (b) forced displacer. The free displacer uses a form of natural tuning to control the engine. The mass of the displacer acting against a gas spring provides the control parameters. The spring constant can be varied by changing the volume of the cavity containing the "spring" gas (bounce chamber). This is generally a very sensitive control parameter, so that small changes in bounce chamber volume can cause large changes in power output. The forced displacer overcomes the problems of the free displacer by providing good control. Many different schemes can be used to provide the drive for the displacer. These include:

- Hydraulic actuator
- Separate crankshaft (not connected to power piston)
- Solenoid (electrical actuation).

A hydraulic actuation system has been used in the heart power source and for the output on a 15 kW conceptual design. The hydraulics add complexity and cost to the system. A solenoid drive is the simplest system and does not require any seals. The electrical drive for the displacer can be automatically controlled to compensate for load changes and start-up. The simplicity of the solenoid drive made it the preferred system for the engine/alternator unit.

Three working gasses, helium, hydrogen, and air, were considered. Air was determined to be undesirable due to the low power density that can be achieved witn its use. The safety of helium versus the slightly improved performance of hydrogen was a trade-off consideration. Other considerations were the difficulty in containing hydrogen and the effects it has on metal properties. The result of these considerations was the conclusion that helium was the best all around working gas.

C. Conceptual Design of a 3 kW Stirling Ringbom Generator System

The complete generator set will consist of:

- Operator control and indicator lights.
- Starting system, including igniter.
- Fuel system, including liquid fuel control.
- Combustor.
- Sodium heat pipe.
- Two-phase cooling system and fan.

- Noise and infrared attenuation devices.
- Engine/alternator subassembly.
- Control system and microprocessor.
- Mounting frame.

Operator Control and Indicator Lights

Flow will use an operator control system that is the ultimate in simplicity...an on-off switch. The operator will also be provided with several indicator lights to display the status of the system. These lights are used as diagnostic indicators to help the operator troubleshoot the system.

Starting System, Including Igniter

The starting system will be fully automated, and will operate the entire system from battery power until the generator comes on line. The battery will power the displacer drive (400 watts), the fuel pump and combustor air fan (60 watts, total), the combustor ignition system (300 watts, for a short period during initial ignition stage), the microcomputer (5 watts), the oil pump (35 watts), and, as required, the Stirling engine cooling fan (150 watts). The system will include an inverter (12 volt DC to 120 volt AC) to operate these auxiliary units more effectively during startup. A conventional automobile battery can supply ample energy with reserves many times the operational requirements.

The start switch turns on the microcomputer, which in turn will sequentially activate the other controls to start the system. We will also provide a ready light to indicate when the system is ready for application of the electrical load. This ready light will also signal the transfer of the auxiliary electrical load from the battery to the generator, which will then recharge the battery.

Fuel System, Including Liquid Fuel Control

The fuel system consists of a tank, pump, and controls. The fuel control system will be operated by a microprocessor. Flow Industries' recent success in incorporating a microprocessor into the design of our 120-kW vertical axis wind turbine, and the general usage of microprocessors in automotive fuel control, indicates its use in the present application. Our approach is to use the microprocessor to provide a combination of continuous and intermittent fuel feed. Continuous fuel feed will be used from 100% down to about 40% of design loading. Below the lower load level, we recommend intermittently shutting off the combustor completely, allowing the thermal inertia of the combustor and heat pipe to power the engine. During continuous operation, the microprocessor will control fuel flow rates and fuel temperature to achieve optimal combustor efficiency over the load range. The transition point from continuous combustor operation to on/off operation will be determined by comparing fuel consumption under various engine loads for each of the two modes of operation.

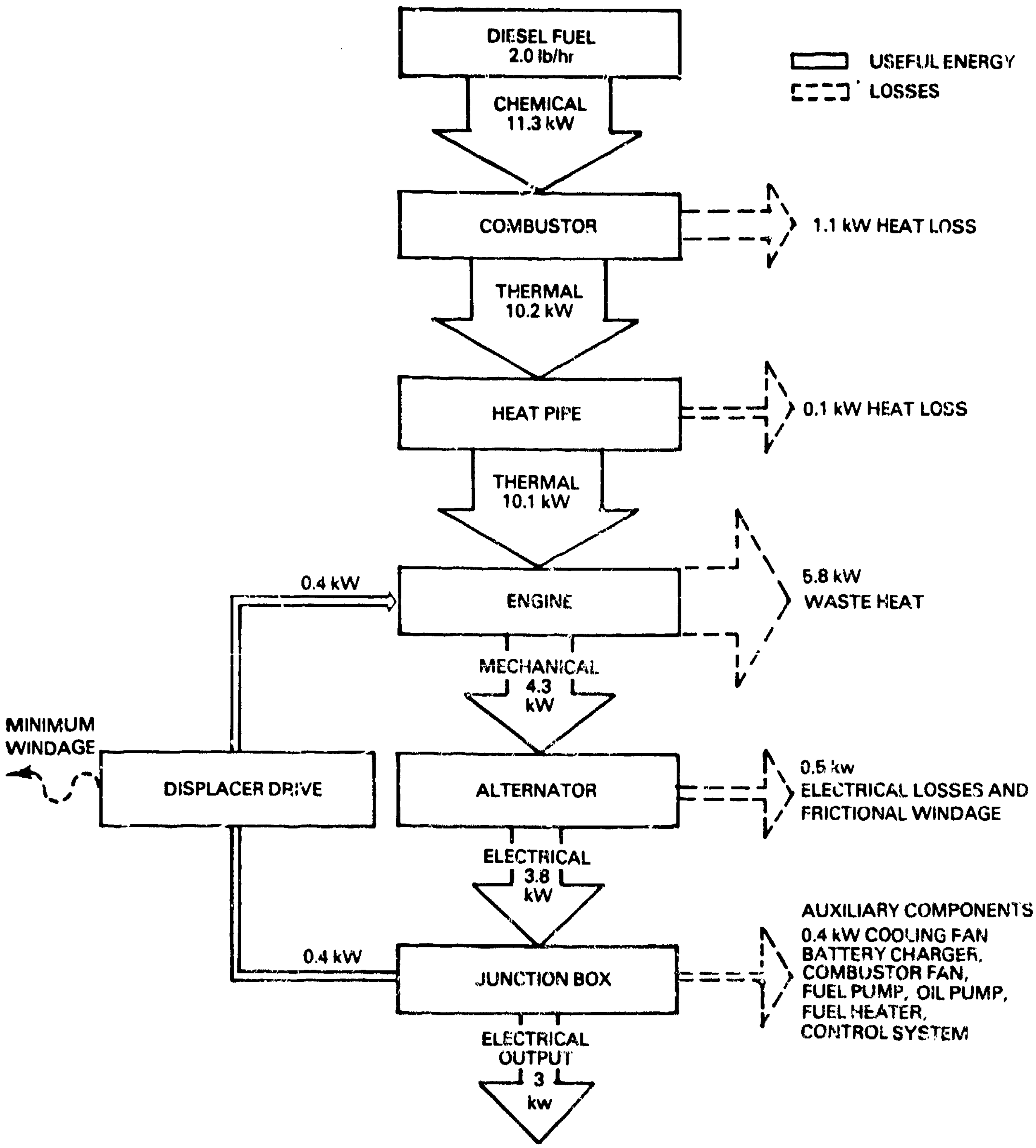
The microprocessor will use measurements of the heater head temperature and the electrical load to determine the fuel flow rate. The heater head temperature will be maintained at the design point for efficient operation, but the rate of head heating or cooling will vary with engine loading. Thus, by monitoring the heater head temperature, and using the change in the electrical load as a derivative feedback, a responsive, stable control of the combustor can be assured.

The microprocessor will also be designed to vary the combustor air flow rate by varying fan speed in a manner similar to liquid fuel control. The air flow will be varied in proportion to the fuel flow in order to achieve the high flame temperatures associated with near stoichiometric combustion.

Combustor

We propose the use of a modified furnace combustor to supply the 11.3 kW or 38,000 BTU/hour of thermal energy to develop 3 kW (4 HP) of electric power, as shown in Figure 6. Figure 6 shows the individual components, their power losses, and the energy flow throughout the entire system.

Recent interest in fuel-efficient home furnaces has resulted in several new combustor designs far superior to older models. The new designs, incorporating flame retention burners, have fuel-to-thermal conversion efficiencies up to about 90%. The remaining inefficiencies result from the latent heat of vaporization contained in the water vapor. We will investigate these new combustor designs in Phase 2, and modify one of them for use with this system. One of the planned modifications will be a combustor-air preheater to recover the heat contained in the combustion gases leaving the hot sodium heat pipe evaporator. This is necessary to achieve high fuel-to-thermal energy conversion efficiencies in heating sodium. The 3 kW output



Energy Flow Chart for 3 kW Forced Displacer Ringbom Stirling Generator Unit

Figure 6

fuel consumption is 2 pounds per hour (1.1 liters per hour) of diesel fuel. This corresponds to 0.5 pounds per horsepower-hour.

Thermostatically controlled electric fuel preheaters are also commercially available. Since fuel temperature directly controls the fuel droplet size in the combustor, use of such a preheater will facilitate efficient combustion.

Most existing Stirling engines use hot combustion gases to directly heat the heater head on the hot end of the displacer, resulting in inefficiencies and mechanical problems. The combustion gases, having a low heat transfer coeffiecient, require a surface area much larger than the heater head for efficient heat exchanging. This results in excessive heat loss or an excessively large heater head. A second problem results from nonuniformities in the flame temperature of the combustor, caused by local variations in fuel-to-air ratios. The hottest places in the flame can overheat the heat exchanger tubes, weakening them and causing blowouts of the high pressure working fluid of the engine. To prevent these hot spots, the overall flame temperature must be lowered, which results in a loss of combustor efficiency. In addition, the tube walls must be made thick, which results in excessive thermal stresses, thermal fatigue, and eventual failure of the tube wall.

The use of a liquid metal heat pipe to conduct the combustor energy to the displacer piston avoids previously mentioned problems, and provides several positive advantages. First, the heat pipe acts as a thermal transformer. It gathers heat from hot combustion gases over a wide area that has a low heat-transfer coefficient, and delivers the heat across the much smaller area of the heater head to the engine working gas, which has a high heat-transfer coefficient. This allows the heater head to be about one-third the size of a combustion-heated heater head, with an accompanying reduction in weight, volume, and cost. Second, the heat pipe acts as an isothermal heat receiver since it cannot be damaged by local hot spots due to the high thermal conductivity of the liquid metal. This allows the use of thinner tube walls, which results in weight reduction, and faster, more efficient heat exchange. The fluid of choice in the heat pipe is liquid sodium, due to its easy availability and appropriate boiling point for this application. The heat pipe design can be simplified if the heat source is located below the heater head so that the condensed liquid can be returned to the pool by gravity flow rather than by wick action. An area of consideration in heat pipe design is the effect of hydrogen permeation. If hydrogen from the combustion gases permeates the heat pipe walls, the sodium boiling point will rise until the heat pipe requires higher temperatures to begin conducting. Proven coatings to prevent this permeation are available and will be applied as required.

The pressure stabilized configuration employed in Flow Industries' advanced heater head will incorporate a high temperature sodium heat pipe to transfer heat from the heat source to the gas heater region. Hot spots that cause serious problems in other designs are thereby eliminated. In the proposed engine, a wall temperature drop of 20°C is predicted. This is only slightly higher than typical average values experienced by conventional heater tubes, but is much less than the additional 50°C to 100°C temperature difference usually encountered between the hottest metal temperature and the average temperature. A higher average temperature can consequently be achieved with substantially lower peak metal temperatures. This allows the use of less expensive nickel-based alloys instead of the cobalt-based alloys found on currently available Stirling engine designs. This transition significantly reduces the material cost for the heater head with little or no loss in effective hot gas temperature.

The use of high temperature heat pipes also enables the gas heater to be sized for the working gas side of the heat-transfer film coefficient rather than the lower combustion side coefficient. This factor results in less gas dead-volume, which improves the power density of the system. Further performance gains are possible, because an annular flow heat exchanger has a better ratio of heat transfer capacity to fluid-friction loss than tubular heat exchangers with the same dead-volume.

Safety is another important consideration in the heat pipe design. The liquid sodium planned for use is chemically active and reacts strongly with water. Nevertheless, it can be used with complete safety by welding the sodium into a hermetically sealed chamber. Flow's patented heater head design allows all-welded construction to ensure an effective chamber seal. This method is currently used in many diesel engines for exhaust valve cooling. Any safety problem reduces to providing mechanical integrity for the liquid metal container.

Many steel alloys are suitable for containing sodium, and corrosion resistance to sodium has been well documented by the nuclear industry. Basically, the same iron-nickel-chromium alloys used for high temperature creep resistance are applicable for containing sodium.

Since the Army's long range requirement for the combustor includes the use of alternate fuels, fuels such as diesel, jet fuel, and gasoline can all be burned efficiently in the flame retention burners by making minor adjustments.

Sodium Heat Pipe

Two major problems with existing combustion-driven Stirling engines are the physical size of the heater head and hot spot damage to the heat exchanger tubes. The use of a sodium heat pipe to conduct the combustor energy to the displacer heater head has advantages for two basic reasons. First, the heat pipe acts as a thermal transformer, collecting combustor energy over a relatively wide area and delivering it to a compact heater head. Second, the heat pipe is essentially an isothermal heat receiver and cannot be damaged by local hot spots in the combustion flow.

Two-Phase Cooling System and Fan

The cold end of the displacer piston will be most efficiently cooled with either a heat pipe using halogenated hydrocarbons or a two-phase thermosiphon using one of the pentane isomers. In either case, no cooling pump will be required, thus avoiding a known high-maintenance item in conventional internal combustion engines. The preferred cooling method will be selected based upon considerations of reliability and ability to operate over the broad range of ambient temperatures encountered (-25°F to 125°F).

It will be necessary for the evaporator end of the coolant cycle to surround the cold end of the displacer piston. The condenser end of the cycle would best be situated above the displacer in a radiator that is cooled by forced-air convection with a fan or blower.

The cooling fan will need to draw about 7000 watts from the coolant. It will operate at reduced air flow velocities to prevent excessive noise generation. To further reduce noise, special muffling devices could be installed with the objective of meeting the aural non-detectability requirement as specified in MIL-STD-1474b. Similar muffling devices could also be installed on the combustor air intake and exhaust.

Noise and Infrared Attenuation Devices

The design goal for noise level is to achieve the limiting octave band levels (dB) as specified in MIL-STD-1474b for aural non-detectability at a nominal distance of 100 meters. To achieve this, the engine noise level measured at a distance of, for example, 6 meters should not exceed 45 dB for the octave band having a center frequency of 500 Hz. Design features emphasizing low noise could be incorporated, in addition to special muffling devices in order to meet the Army's requirements for an extremely low noise level power source. Special considerations need to be focused on the combustor air intake and exhaust, cooling fan and its shroud. Lightweight infrared radiation shields could be incorporated to reduce the infrared signature.

Engine/Alternator Subassembly

After a comparative analysis of the five Stirling engine concepts was completed, the forced displacer Ringbom Stirling was chosen, based upon the previously listed advantages, found in Table 5.

The proposed design concept employs a helium working fluid and an electromagnetically driven displacer. Frequency control is accomplished by means of a crystal-based electronic displacer drive. The design also employs a rotary electrical device so that both A.C. and D.C. machinery can be incorporated. System balancing is accomplished by using harmonic dampers and counterbalances. The system is designed to be hermetically sealed, similar to a refrigeration unit, for maximum reliability.

Preliminary engine specifications and a full-size conceptual layout are shown in Table 6 and Figure 7. The key elements of the design are discussed below.

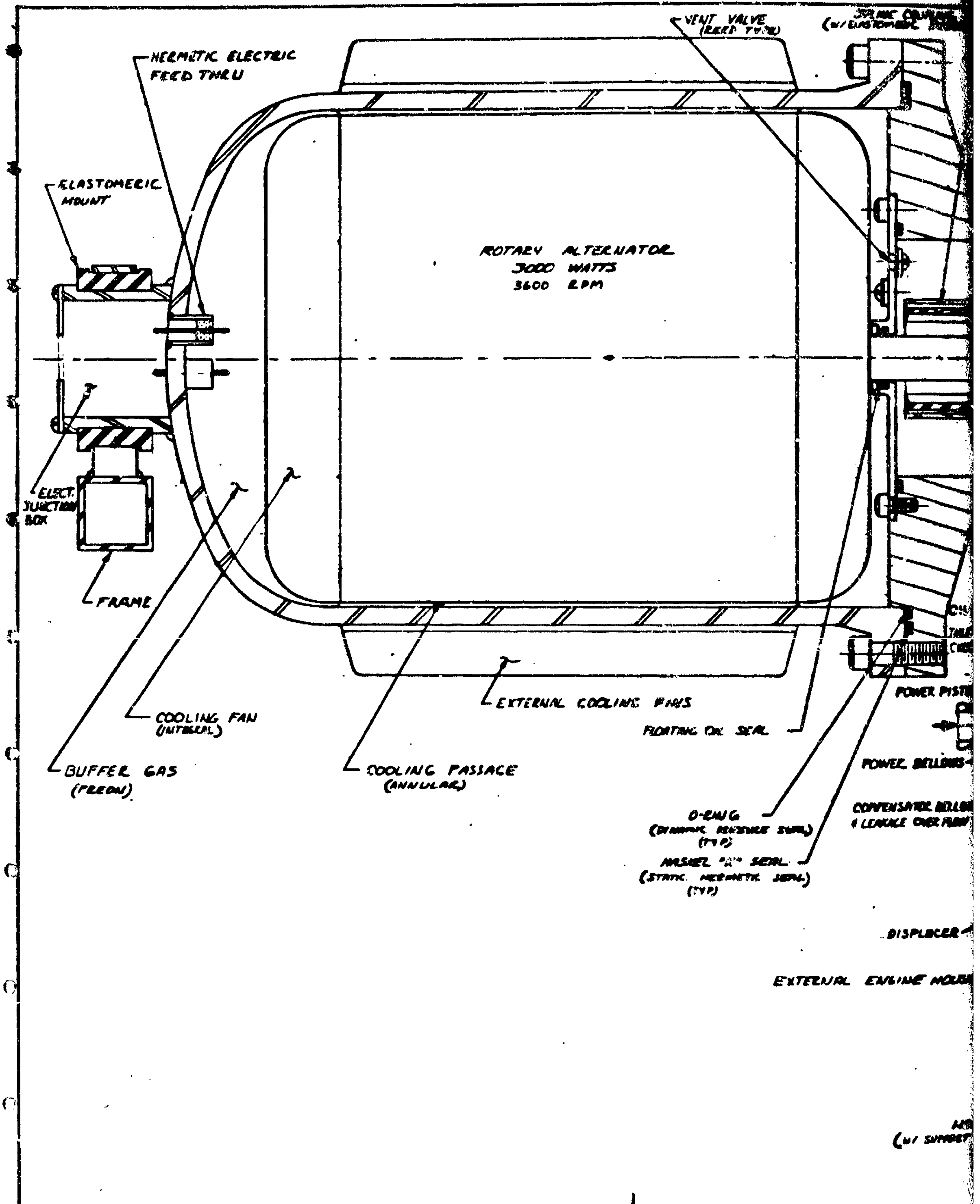
The displacer is held concentric within its housing by means of double spiral flexures at each end, allowing free axial motion while maintaining a constant gap between displacer and housing. The basics of this concept are shown in Figure 8. The displacer drive consists of a crystal-controlled electromagnetic system that drives the displacer at a constant 60 Hz, once the engine is brought up to full operating speed.

The working gas is heated by heat pipe condensate which collects on the walls of the concentric tubes through which the working gas passes.

The working gas moves to and from the cooler region through an annular regenerator.

Table 6. Preliminary Engine Specifications 3kW/60Hz Ringbom GPU

Displacer:	
Diameter	6.35 cm (2.50 in.)
Stroke	1.27 cm (.50 in.)
Displacement	40 cc (cu. in.)
Power Piston:	
Diameter	5.72 cm (2.25 in.)
Stroke	1.17 cm (.46 in.)
Displacement	30 cc (1.83 cu. in.)
Regenerator:	
Outside Diameter	7.30 (2.88 in.)
Inside Diameter	6.68 cm (2.63 in.)
Length	3.81 cm (1.50 in.)
Volume	26.6 cc (1.62 cu. in.)
Matrix Density	40% to 50%
Working Gas:	
Flow gap (heater and cooler)	.064 cm (.025 in.)
Pressure	13.8 ± 5.5 mpa (2000 ± 800 psi)
Gas	Helium
Buffer Gas:	
Pressure	13.8 mpa (2000 psi)
Volume (min. required)	1 liter (61 cu. in.)
Gas	Freon
Alternator:	
Max Continuous Power	3000 watts
Frequency	60 Hz
Speed	3600 rpm



VENT VALVE
HERMETIC ELECTRIC
FEED THRU
ELASTOMERIC
MOUNT
ROTARY ALTERNATOR
3000 WATTS
3600 RPM
ELECT.
JUNCTION
BOX
FRAME
EXTERNAL COOLING FINS
FLOATING OIL SEAL
COOLING FAN
(INTEGRAL)
BUFFER GAS
(FREON)
COOLING PASSAGE
(ANNULAR)
POWER BELLOWS
O-RING
(TYP)
DISPLACER

½ Size

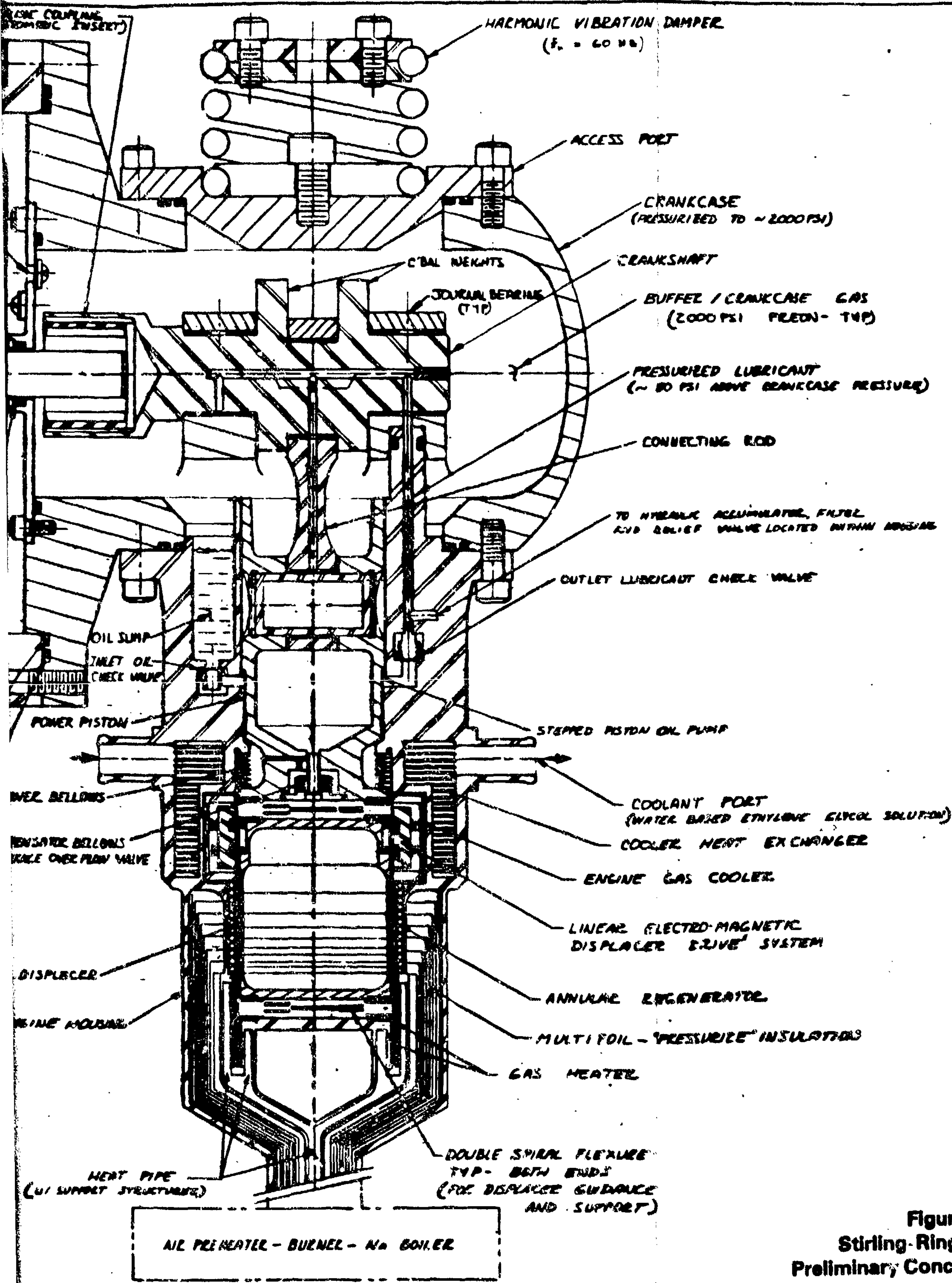
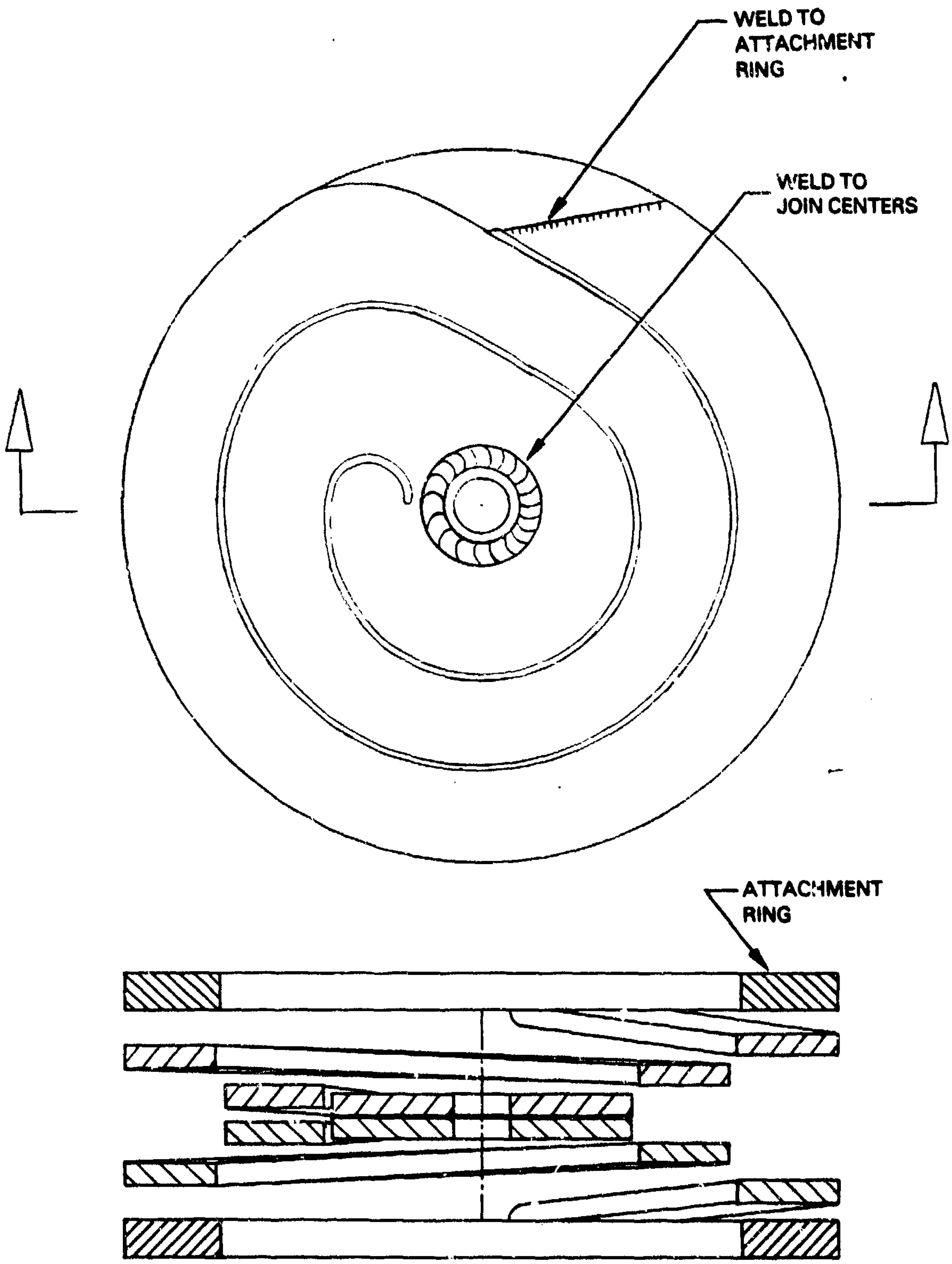


Figure 7
Stirling-Ringbom GPU
Preliminary Conceptional Layout



Displacer Support (Flexure)

Figure 8

The working gas will operate at an average pressure of 2000 psi and will vary ± 800 psi during each cycle. In order to reduce power piston loads, the crankcase will be charged with a buffer pressure of 2000 psi.

The power piston is hermetically sealed with a power bellows that separates the working gas from the crankcase. Indefinite life can be obtained from a bellows that is operated free from any pressure difference. Therefore, a compensator bellows is used to communicate the working gas pressure to the inside of the power bellows. The volume inside the power bellows is oil-filled, and the volume remains constant during operation. Any leakage from this zone is replenished by an oil lubrication pump, discussed below.

The power piston overlaps the stroke of the displacer, producing a negative dead volume for the working gas. This concept increases the power-to-volume ratio of the engine, minimizing size and cost.

The power piston is designed with a diameter step that becomes the oil lubrication pump during operation. Oil is drawn from the sump through a check valve during the up stroke and forced through another check valve to the journal bearings during the down stroke. An accumulator, relief valve, and filter (not shown on the drawing) are connected to the oil pump output to maintain a constant 50 psi above buffer pressure during the up stroke and to remove wear particles.

The crankshaft is balanced to minimize vibration. A harmonic vibration damper tuned to a natural frequency of 60 Hz is mounted externally to balance the vibration induced by the power piston and displacer.

Since it is extremely difficult to seal a gas through a moving seal, the alternator is contained within the system and surrounded by the crankcase gas at 2000 psi. Electical connection is then made through a hermetic seal. This concept is similar to a refrigerator compressor that is hermetically sealed and reliably operates without maintenance for many years.

The design incorporates metal-to-metal hermetic "K" seals that are well-proven static seals. An additional elastomeric seal is used with each "K" seal to damp out the pressure fluctuations of the buffer gas, eliminating fatigue.

A sealplate separates the alternator housing from the crankcase, preventing unwanted intrusion of engine oil into the alternator housing if the GPU is inadvertently turned over. The oil sump, however, is designed to allow 30° tilting in any direction.

The advanced-design shaft coupling provides extensive trouble-free life by virture of the spline-elastomer design.

The hardware concepts incorporated in this unit are fundamentally maintenance free. However, access is provided by easy disassembly via the O-rings and "K" seals.

Control System and Microprocessor

System control is based on a microprocessor. With the microprocessor, Flow's system is less expensive and more reliable than it would be without it. Also, it actually aids design by substantially reducing development time. This means of control allows a wide variety of parameters to be sensed and controlled by a relatively simple electronic circuit. This simplicity means that the system is also reliable. Since all of the electronics can be contained on one or two small plug-in printed circuit boards, maintenance can be easily accomplished in the field by a simple board substitution. The board cost should be so minimal that defective boards could be scrapped and several spare boards stocked.

Flow Industries, Inc. has designed and used microprocessor control systems for other high technology field devices, the most notable of which is a 120 kW vertical axis wind turbine that we manufacture commercially. The control system monitors the operating parameters and the power quality of the machinery. It controls the generator and will shut the system down in case of problems with the turbine or the ·r grid. The turbine control system is much more complicated than the control sy· ·m anticipated for the Stirling/Ringbom Engine (FPSE) generator system, yet it onl· ·equires four small printed circuit boards. The flexibility and reliability of this control system has proven to be a key feature of the entire wind turbine system.

Th· key features of the proposed Stirling alternator controller are covered in the follow··g sections, which also provide some insight into the control algorithm which will be designed. The overall philosophy is to provide a control system that will not require the operator to do anything more than turn on a switch to start the system, and turn it off to shut the system down. Figure 9 shows a schematic of the control system.

In order to meet the frequency and voltage stability requirements, the control system must have an accurate frequency reference and a rapidly responding set of sensors and controls. These must provide the proper response to compensate for such phenomena as the thermal inertia of the system, and control actuator response time.

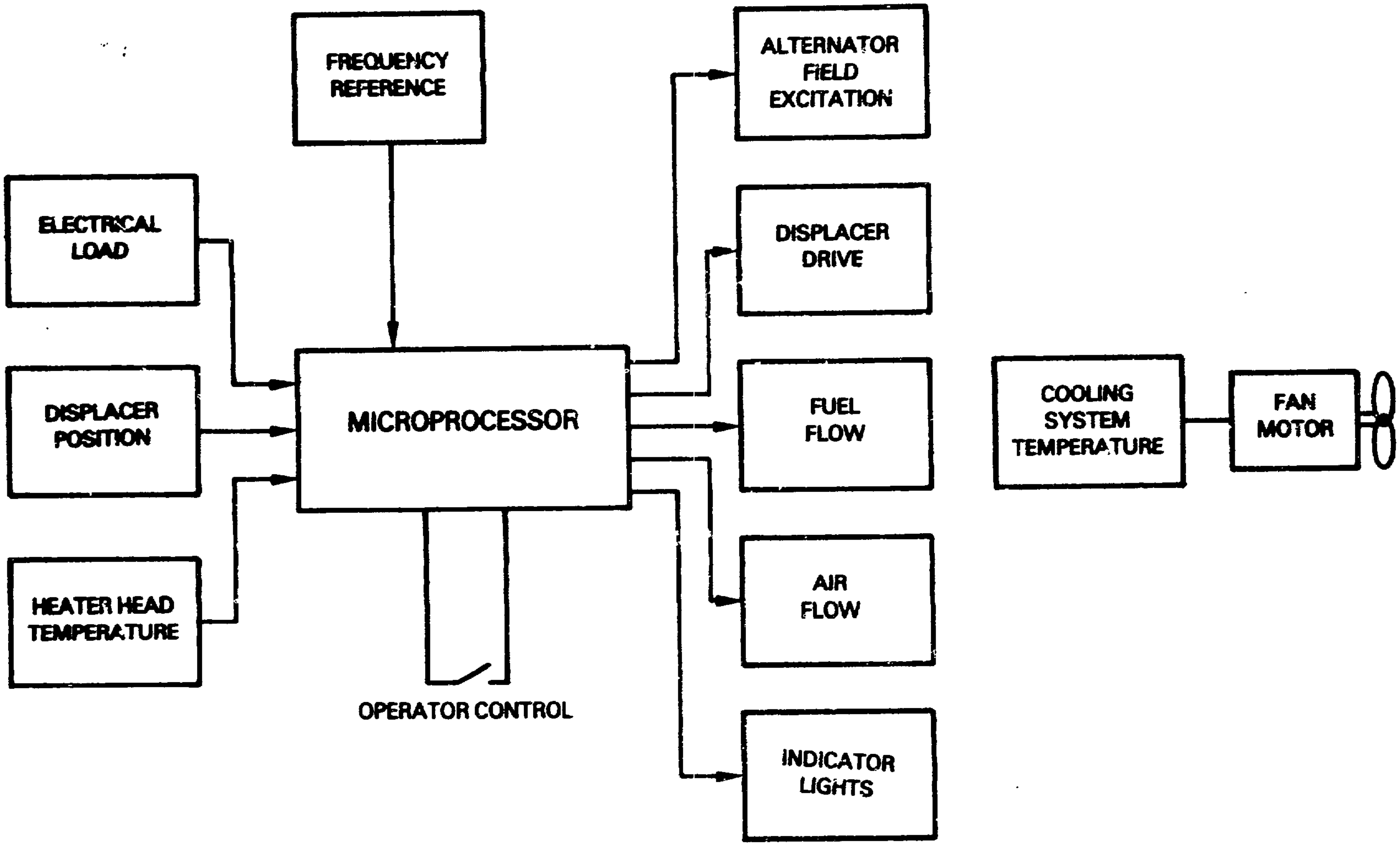


Figure 9. Schematic Control System for Forced Displacer Ringbom Stirling Engine

The sensing and control parameters relating to the Stirling/Ringbom generator system follow:

1. Frequency
2. Load (current/voltage)
3. Displacer Amplitude
4. Fuel Flow
5. Air Flow
6. Heater Head Temperature
7. Cooling System Temperature
8. Oil Pressure

These parameters define a control system that meets all requirements for power quality.

The sensors for the system must be rugged and have a response time rapid enough to provide a stable system response. Five sensors have been identified for the proposed system. All of these sensors are available from several manufacturers and do not pose any design problem.

1. Voltage - the output voltage of the alternator is a key parameter that must feed back to the excitation current. The proposed sensor is an analog-to-digital (A/D) convertor that would either provide an instantaneous voltage value or an RMS value over a given time interval. Using the instantaneous value allows for more flexibility and tighter control from the microprocessor, and may be the desired mode of operation.
2. Current - the current can be sensed in the same manner as the voltage by using a shunt resistor and an A/D convertor. The current provides a rapid indication of the fuel flow requirements, and can be used as an effective "rate" input to the fuel flow control algorithm.
3. Heater head temperature - the most common temperature sensing element for such applications is a thermocouple. These devices provide rapid response times and are accurate enough for the control purpose. Again, an A/D converter can be used to convert the signal into a form usable for the microprocessor. The heater head temperature must be maintained between predetermined limits for best efficiency and system life.

4. Cooling system temperature - this sensing device can be a simple bimetalic contact with some hysteresis which controls the fan motor. Several automotive devices are available.
5. Oil pressure - there are several automotive devices available.

The control system must operate five devices that regulate:

1. Displacer motion.
2. Fuel flow.
3. Air flow (for combustion).
4. Cooling system fan.
5. Operational indicator lights (e.g., warning lights).

The displacer motion is controlled by the current applied to the linear motor drive system. The displacer motion amplitude will be a function of the electrical load. Under steady operating conditions, the frequency will be held constant by reference to a crystal oscillator. During starting, the displacer frequency will be gradually increased to steady operating conditions. The displacer motion is controlled to maintain the correct stroke, that would otherwise vary with phase angle between displacer and power piston.

The fuel flow and combustor air flow are proportional control valves that will be driven by the microprocessor to produce maximum combustion efficiency. For idle load operation, the combustor will be operated intermittently to achieve optimum performance.

The cooling system fan is driven by an electric motor controlled by a bimetalic switch. The system is simple and similar to that found in many modern automobiles.

The operational indicator lights are a group of display lights that inform the operator of system status. Their main function is to aid in trouble-shooting the system should some problem arise.

The control system handles four operating regimes:

1. Start-up.
2. Steady state operation.
3. Transient loads.
4. Shut-down.

The control system design philosophy is to reduce the operator's function to one of turning a single switch on or off. This means that the control system logic will make all the decisions appropriate to proper system operation, determine if there are any problems, and take the necessary action. The microprocessor controller will provide diagnostics to help troubleshoot the system. For example, if oil pressure is lost, the controller will shut the system down and illuminate a light to inform the operator of the problem. Many other conditions can be identified and provisions made for appropriate warning lights. This is the technique used on the wind turbine previously mentioned. Such a system greatly simplifies maintenance.

Transient loads are sensed to control displacer amplitude and the combustor fuel and air flow.

During shut-down, the load will be protected from any low voltage operation by an internal relay, which disconnects it. Also, the cooling system must continue to operate until there is no danger of overheating the engine.

Mounting frame

The entire operating system will be mounted on a sturdy metal frame. The individual components will be positioned to minimize system volume and be protected from damage and deterioration as per MADi AK military specifications.

D. Computer Simulation

The Flow Stirling engine design procedure is well grounded in theory and has been successfully used over and over again at the practical level. This has been demonstrated by the successful design of systems developed over the years by Flow Industries and its team members.

The general computer simulation codes and procedures were modified to simulate the 3 kW Ringbom engine with linear electric drive.

The analytical procedure involves two separate programs. The first code, CSMP, performs a dynamic simulation of the system; the second, ASHES, evaluates the thermodynamic performance of the system based on the dynamic simulation result.

The dynamic simulation program calculates displacer and power piston position and pressures as functions of time, by solving a system of differential equations.

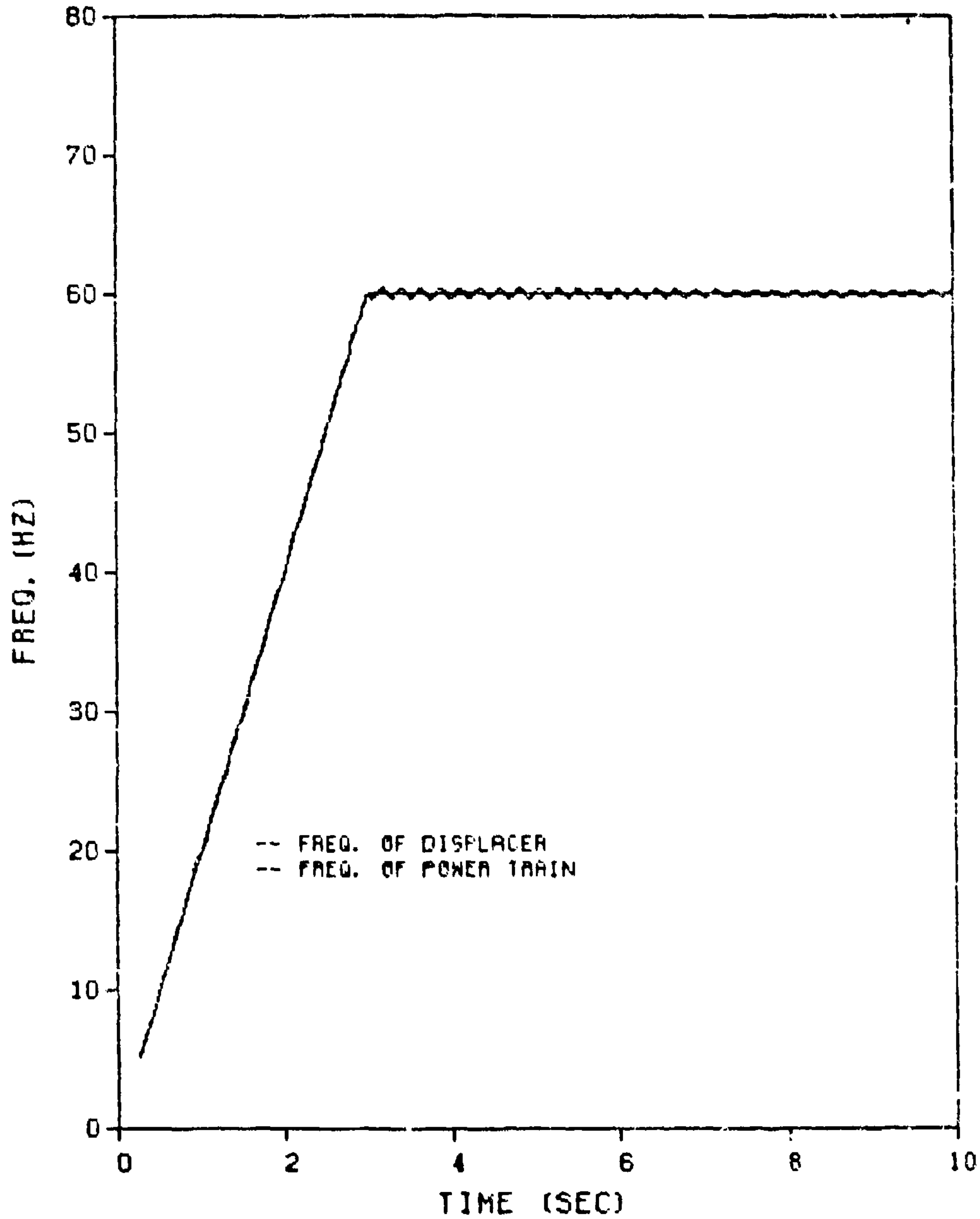
When a dynamic simulation run is completed, the results must be interpreted to determine the work output of the engine, the heat input requirements, and other important design parameters. ASHES (Analysis of the Stirling Hydraulic Engine System) was developed to access the CSMP output files and produce a cycle-by-cycle analysis of the heat input terms and other essential analyses. ASHES eliminates most of the manpower which otherwise would be expended in determination of the predicted design performance for each simulation run.

ASHES provides a concise output listing which includes all the input data used by the simulation, all important calculated initial value parameters for the simulation case, and a complete performance analysis of the simulation run on a cycle-by-cycle basis. The performance analysis includes the pressure-volume integrations necessary to determine work terms and the Second Law heat. Stroke lengths and relative positional data are calculated. ASHES uses simple, second-order thermal analysis methods to calculate the reheat losses, and uses a test data curve fit to calculate the fixed heat loss. ASHES also computes the "instantaneous" frequency of the power piston at each cycle, from which the electrical power output can be determined.

The computer simulations were performed to model the start-up, transient behavior, and the steady power characteristics. Figure 10 shows a plot of the displacer and power piston frequency as a function of time. The starting procedure was to linearly increase the displacer operating frequency from 0 to 60 Hz over a three second period. The figure shows that the power piston closely follows the displacer frequency up to the steady operating condition. There is a slight frequency ripple which is damped. This ripple has an amplitude of about 1% of the 60 Hz steady value initially, and then quickly damps out. This means that the voltage output from the generator and harmonic content would be well within the military standards for tactical power units.

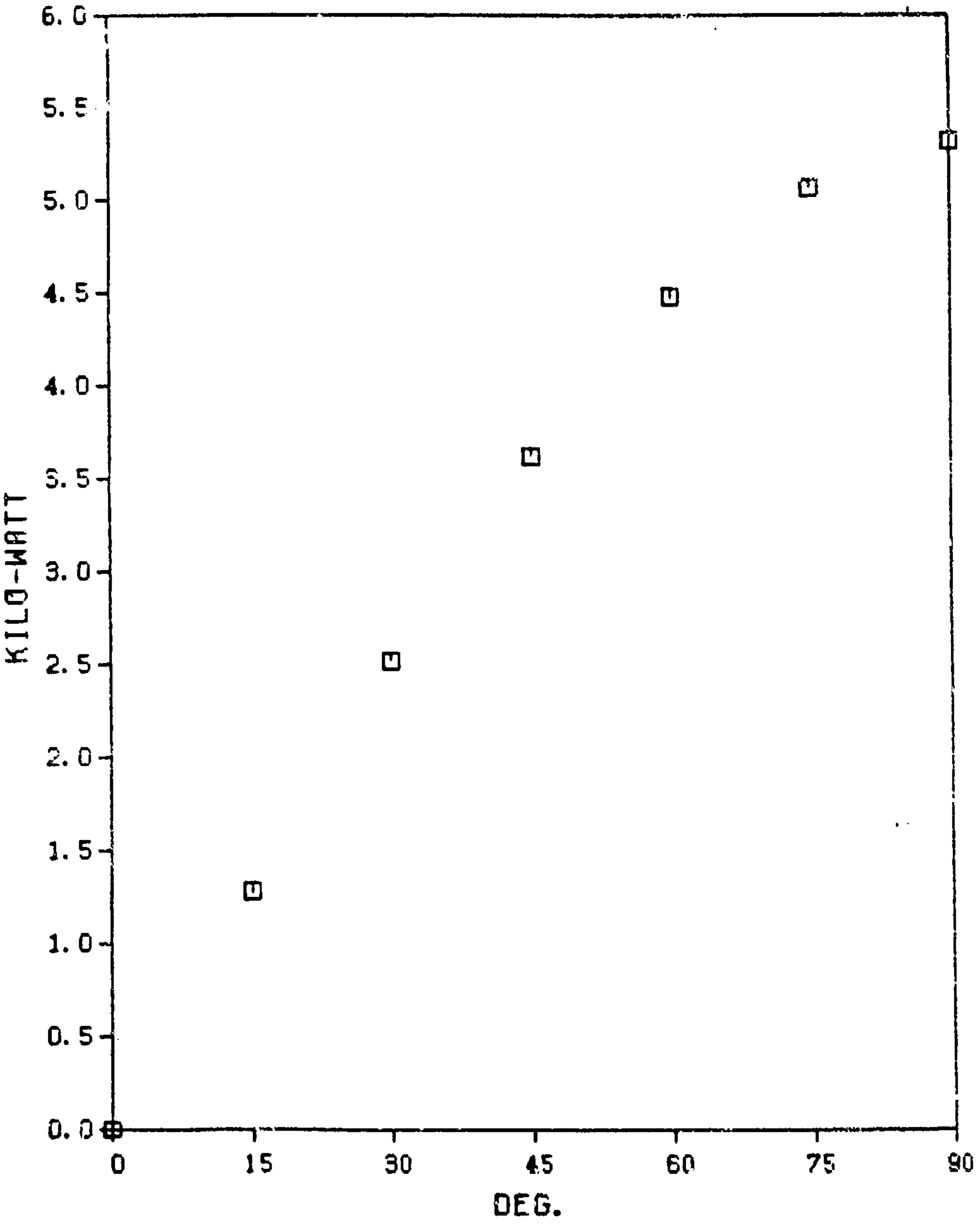
The ramp in frequency for starting will be produced by the microprocessor controlier. Since the microprocessor is crystal controlled, the steady state frequency of 60 Hz will be very precise.

Figure 11 shows the power output from the Stirling/Ringbom engine as a function of the phase angle between the displacer and the power piston. Maximum power is achieved at a 90° phase angle. At the nominal engine power output of 3.8 kW (3kW electrical output plus 0.8 kW for accessories) the operating phase angle is 47°.



Displacer and Power Piston Frequency as a Function of Time

Figure 10



Power Output from the Stirling/Ringbom as a Function of Phase Angle

Figure 11

Transient performance data are presented as percent deviation of instantaneous frequency from the steady frequency of 60 Hz. These results can be interpreted as a percent voltage variation and also as a percent harmonic content. The oscillation has a frequency of about 4 Hz. The damping is proportional to the applied load, as can be seen by comparing Figures 12 and 13. Figure 14 shows the effect of load rejection. The no-load condition was assumed to be 800 watts of power output from the generator, used to power the combustor blower, fuel pump, cooling fan, battery charger, controller and other auxiliaries.

These results indicate that the system will easily meet the requirements for tactical power generation.

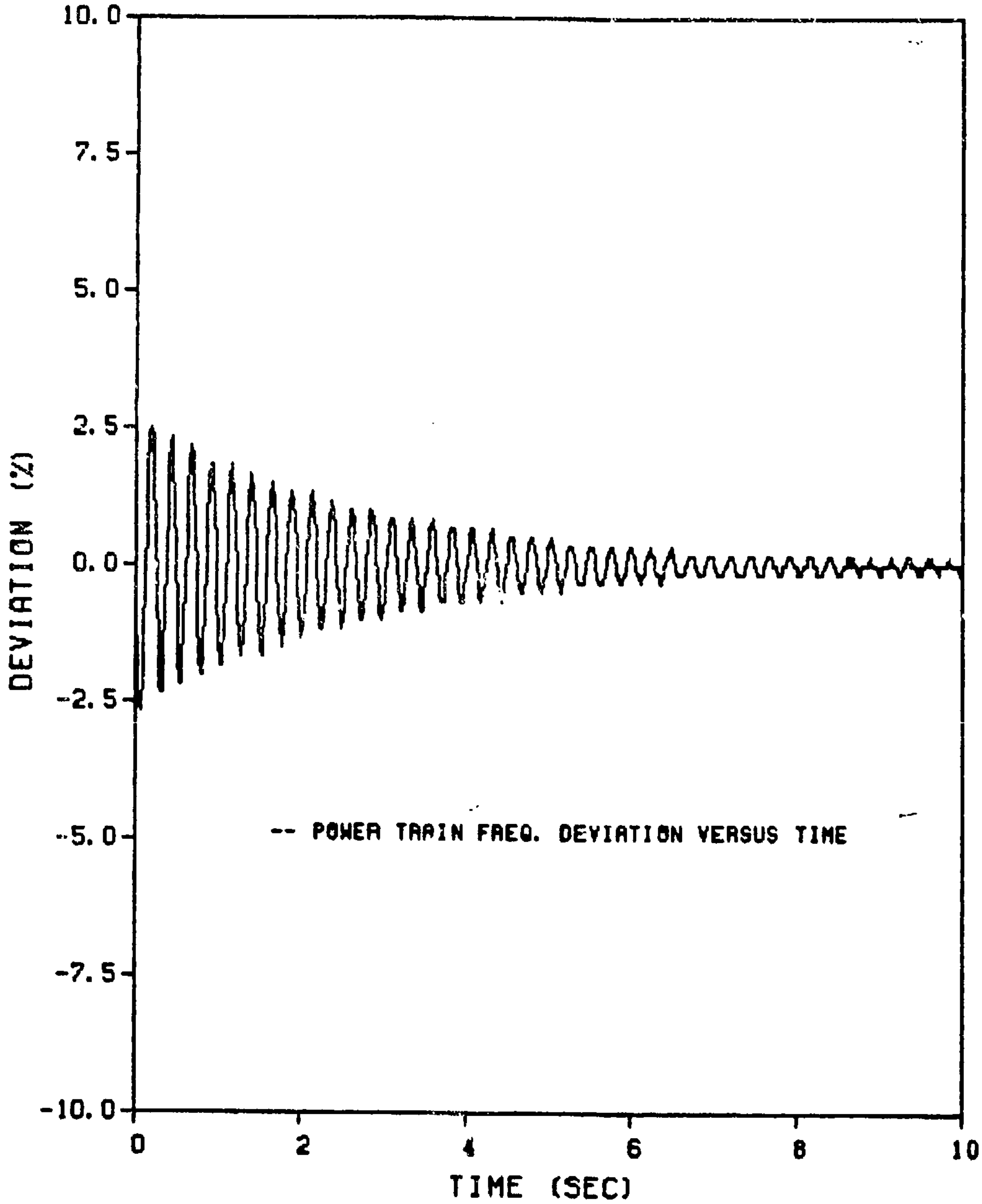
6. CONCLUSIONS

The work presented in this study showed that a long life, maintenance-free Stirling/Ringbom engine design could be built using current technology scaled up from a heart pump power source. The design features a sealed power unit similar to a home refrigerator compressor which would be protected from the environment and not require a working fluid make-up system. The heater head employs a heat pipe to eliminate the burn-out problems associated with prior designs. A two-phase cooling system eliminates the need for a coolant pump, a major source of repair problems. There are no high-pressure sliding seals in the design, which is the main reason that a long, maintenance-free life is projected.

A microprocessor controller insures that the system is always operating at the optimum efficiency and reduces the operator controls to a simple on/off switch. The controller also provides diagnostics to help with field maintenance.

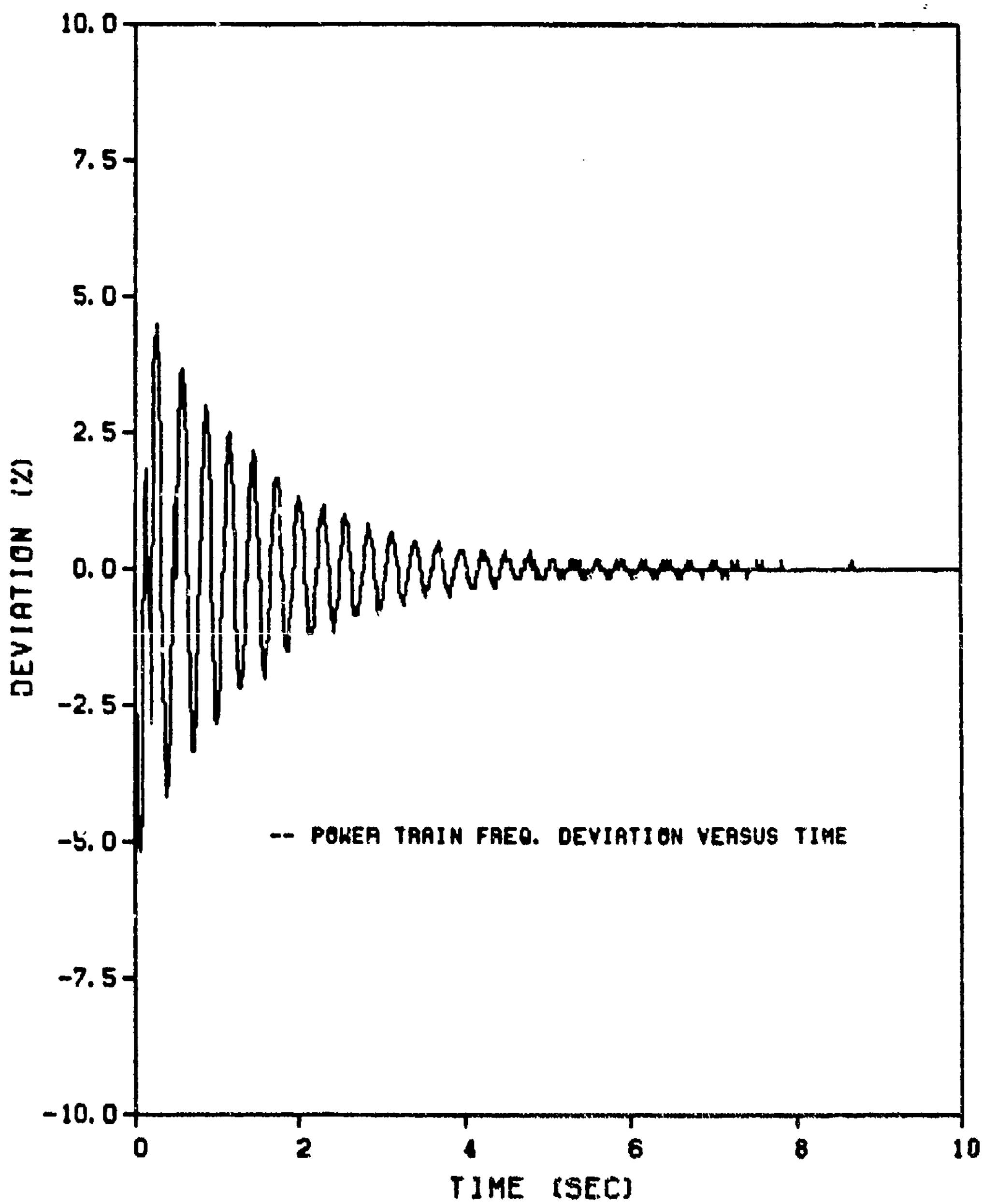
Computer simulations of the design showed that the crystal-based drive for the system provides precise frequency control. The transient load performance of the system far exceeds the tactical generator requirements set forth in MIL-STD-1332B.

The results of this study clearly indicate that a Phase 2 hardware development effort would be justified.



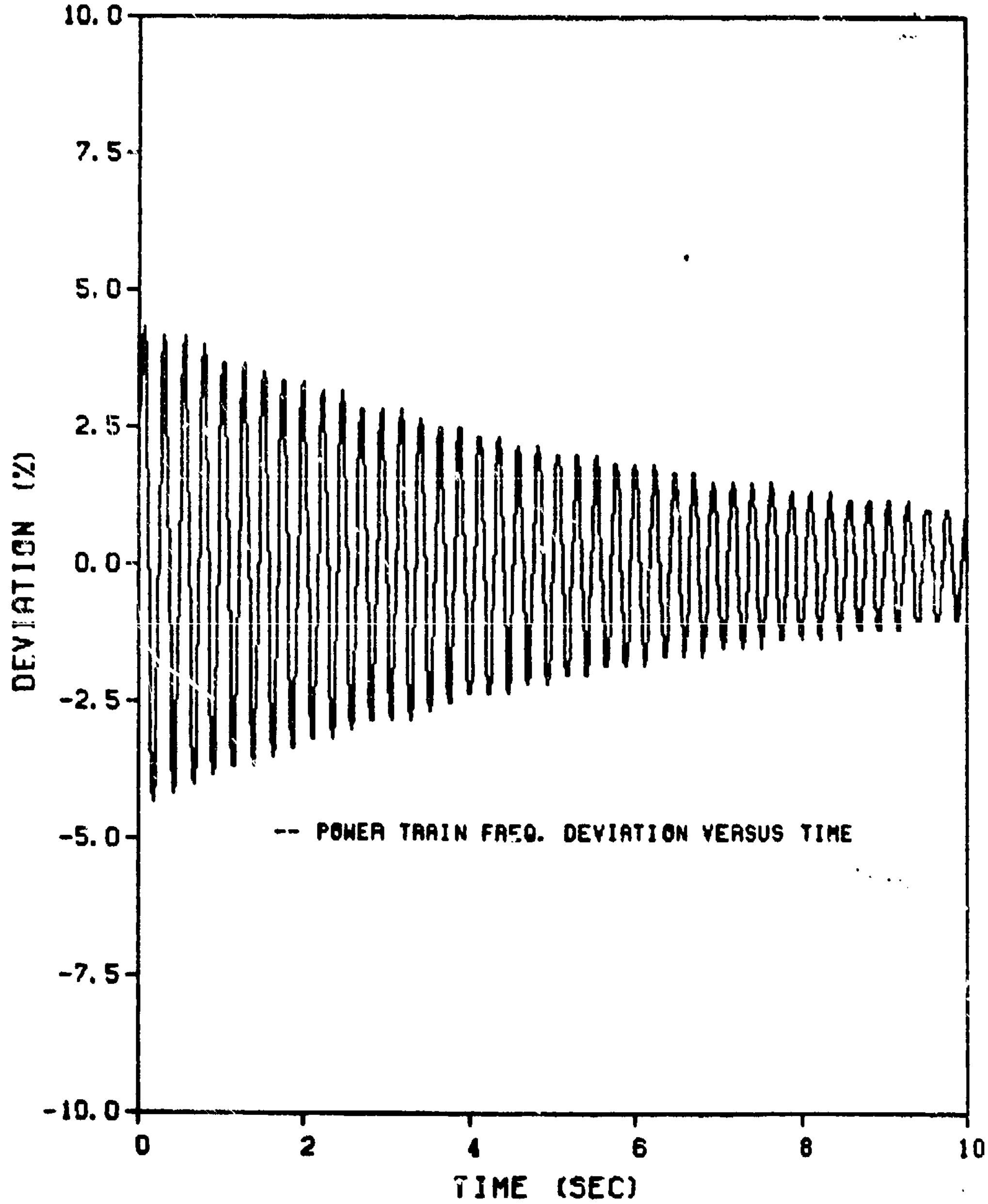
Transcience Performance

Figure 12



Transcience Performance

Figure 13



The Effect of Load Rejection

Figure 14